REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public Reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comment regarding this burden estimates or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188,) Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE 21 July 2003

3. REPORT TYPE AND DATES COVERED
Final Report, 1 August 1999 - 31 July 2003

4. TITLE AND SUBTITLE
Adaptive Transmission Protocols for Mobile Frequency-Hop Radio Networks

5. FUNDING NUMBERS
DAAD19-99-1-0289

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
39007-CI
.18

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Results are reported on research in adaptive transmission for mobile wireless frequency-hop communication networks. Adaptive protocols were devised and performance results were obtained for frequency-hop transmission with Reed-Solomon coding and frequency-hop transmission with turbo coding. A method for generating side information from interleaving was developed, and the performance of Hermitian codes was evaluated. Adaptive transmission protocols were integrated with adaptive routing protocols to provide energy efficiency in mobile, tactical, frequency-hop, wireless ad hoc networks.

14. SUBJECT TERMS
frequency-hop spread spectrum, adaptive transmission, tactical radio networks, packet radio, Reed-Solomon codes, Hermitian codes, turbo product codes

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20030822 156

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

LIST OF MANUSCRIPTS:

Journal Publications:

J. H. Gass, Jr., M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An adaptive-transmission protocol for frequency-hop wireless communication networks," *Wireless Networks*, vol. 7, pp 487-495, September 2001.

T. G. Macdonald and M. B. Pursley, "Staggered interleaving and iterative errors-and-erasures decoding for frequency-hop packet radio," *IEEE Transactions on Wireless Communications*, vol. 2. no. 1, pp. 92-98, January 2003.

T. G. Macdonald and M. B. Pursley, "Hermitian codes for frequency-hop spread-spectrum packet radio networks," *IEEE Transactions on Wireless Communications,* vol. 2, no. 3, pp. 529-536, May 2003.

M. B. Pursley and C. S. Wilkins, "Adaptation of the code rate and transmitter power in frequency-hop communications," accepted for publication in the *IEEE Transactions on Wireless Communications.*

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Integrated routing and adaptive transmission for energy-efficient frequency-hop wireless networks," submitted for publication in the *IEEE Transactions on Communications.*

Book Chapter:

T. G. Macdonald and M. B. Pursley, "Coding for Slow-Frequency-Hop Transmission: Variations on a Theme of McEliece," in *Information, Coding, and Mathematics*, pp. 183-208, Kluwer, 2002.

Conference Publications:

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient routing in frequency-hop networks with adaptive transmission," *Proceedings of the 1999 IEEE Military Communications Conference* (Atlantic City, NJ), vol. 2, pp. 1409-1413, November 1999.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Tradeoffs in the design of routing metrics for frequency-hop wireless networks," *Proceedings of the 2000 IEEE Military Communications Conference* (Los Angeles, CA), vol. 1, pp. 3.1.1-5, October 2000.

J. P. Coon, T. G. Macdonald, and M. B. Pursley, "A new method for obtaining side information in frequency-hop spread-spectrum systems," *Proceedings of the 2000 IEEE Military Communications Conference* (Los Angeles, CA), vol. 1, pp. 5.2.1-5 , October 2000.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient routing in frequency-hop radio networks with partial-band interference," *2000 IEEE Wireless Communications and Networking Conference Record* (Chicago, IL), vol. 1, pp. 79-83, September 2000.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient protocols for mobile wireless spread-spectrum communication networks," *Proceedings of the Sixth International Symposium on Communication Theory and Applications* (Ambleside, UK), pp. 64-69, July 2001.

T. G. Macdonald and M. B. Pursley, "The performance of frequency-hop spread spectrum with Hermitian codes," *Proceedings of the 2001 IEEE Military Communications Conference* (Los Angeles), pp. 40.2.1-5, October 2001.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An improved forwarding protocol for updating channel state information in mobile FH wireless networks," *Proceedings of the 2001 IEEE Military Communications Conference* (Los Angeles), pp. 29.5.1-5, October 2001.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Adaptive protocols for energy-efficient spread-spectrum wireless networks," *2002 IEEE Wireless Communications and Networking Conference Record* (Orlando, FL), vol. 1, pp. 419-425, March 2002.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Alt-forwarding in mobile frequency-hop wireless networks," *2002 IEEE Wireless Communications and Networking Conference Record* (Orlando, FL), vol. 1, pp. 426-432, March 2002.

M. B. Pursley and J. S. Skinner, "Turbo product coding in frequency-hop wireless communications with partial-band interference," *Proceedings of the 2002 IEEE Military Communications Conference* (Anaheim, CA), pp. U405.5.1-6, October 2002.

M. B. Pursley and J. S. Skinner, "Decoding strategies for turbo product codes in frequency-hop wireless communications," *Proceedings of the 2003 IEEE International Conference on Communications* (Anchorage, AK), vol. 4, pp. 2963-2968, May 2003.

M. B. Pursley and J. S. Skinner, "Adaptive-rate turbo-product coding for frequency-hop transmission and time-varying partial-band interference," accepted for publication in the *Proceedings of the 2003 IEEE Military Communications Conference* (Boston, MA), October 2003.

SCIENTIFIC PERSONNEL SUPPORTED:

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Graduate Students: T. G. Macdonald, K. Gajaraj, J. S. Skinner, J. S. Wysocarski

Honors and Awards

Professor M. B. Pursley
IEEE Military Communications Conference Award for Technical Achievement, 1999; Clemson University Alumni Research Award, 2000; Honorary Member, Golden Key National Honor Society, Fall 2000; IEEE Millennium Medal, 2000; Clemson University Board of Trustees Award for Excellence, 2000, 2001, 2003; IEEE Communications Society Distinguished Lecturer, 2001-03; Armstrong Achievement Award, IEEE Communications Society, 2002

Graduate Assistants
T. G. Macdonald, Clemson University Outstanding Graduate Research Award
T. G. Macdonald, AFCEA Doctoral Fellowship
J. S. Skinner, MIT Lincoln Laboratory Graduate Fellowship

INVENTIONS: None

SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS:

Future tactical frequency-hop communication networks should employ adaptive transmission to reduce energy consumption, decrease interference to other terminals in the network, and lessen the probability of detection by unauthorized receivers. The research publications listed in this report advance several new concepts in frequency-hop transmission, present results on the performance of new techniques for the use and development of side information in frequency-hop receivers, and describe an integrated protocol suite that couples adaptive transmission, forwarding, and routing in mobile, tactical, wireless frequency-hop communication networks.

Information about the reliabilities of the received symbols is very beneficial in frequency-hop communication systems, especially those that employ adaptive transmission. This information, known as side information, can be used to erase unreliable symbols at the input to an errors-and-erasures decoder.

For slow-frequency-hop systems it is common that special redundant symbols, referred to as side-information symbols, are included in each dwell interval, and the demodulation of these symbols provides the side information. The corresponding decrease in the number of message symbols that can be sent in each dwell interval makes it desirable to develop alternative methods that do not require side-information symbols. We proposed such an alternative that employs staggered interleaving of Reed-Solomon code words and iterative errors-and-erasures decoding to make erasure decisions without the need for side-information symbols. The information obtained in the iterative decoding process can also be used to characterize the link for the purpose of adapting the code rate and transmitter power to match the channel conditions.

The performance of the staggered interleaving scheme with iterative decoding was evaluated for channels with partial-band interference and compared with the performance of systems that employ standard block interleaving and errors-only decoding or errors-and-erasures decoding with side information obtained from test symbols. In many situations, the staggered-interleaving scheme results in a lower packet error probability than is obtained in a system that employs test symbols. It follows that the staggered-interleaving method also gives a higher throughput in these same situations. The decoding procedures for systems with staggered interleaving and systems with test symbols each require the selection of a threshold. The performance of the staggered-interleaving scheme is less sensitive to the value of its threshold than the performance of the system with test symbols. The staggered-interleaving scheme performs quite well even if the iterative decoding algorithm is limited to three iterations.

Research has been completed on Hermitian codes as an alternative to Reed-Solomon codes for adaptive frequency-hop spread-spectrum packet radio networks. Analytical results were developed for the evaluation of the packet error probability for FH transmissions using Hermitian coding. We find there are several situations for which Hermitian codes provide much lower packet error probabilities than can be obtained with Reed-Solomon codes. Performance evaluations are presented in our publications for an additive white Gaussian noise channel and for certain partial-band interference channels. We evaluated the packet error probability for both errors-only and errors-and-erasures decoding. In general, as the code rate decreases or the symbol alphabet size increases, the relative performance of Hermitian codes improves with respect to Reed-Solomon codes.

When employed in FH packet communications, a single Hermitian code word can replace a number of interleaved Reed-Solomon code words. For example, a packet with 1,536 information bits can be sent as one (512,256) Hermitian code word or eight interleaved (64,32) Reed-Solomon code words. In this example and in several similar examples, the Hermitian code provides a lower packet error probability than the interleaved Reed-Solomon code for communication over the AWGN channel. For a given probability of packet error, the improved performance of the Hermitian code translates to an increased communication range for most applications of FH packet radio networks. For several other channel models, Hermitian codes are superior to Reed-Solomon codes. In particular, for many partial-band interference channels, Hermitian codes give a smaller packet error probability than Reed-Solomon codes.

We have devised an integrated protocol suite for frequency-hop spread-spectrum tactical radio networks that includes adaptive transmission, adaptive routing, and adaptive forwarding. The use of adaptive transmission in wireless, store-and-forward, packet communication networks often results in large differences in the energy requirements of the alternative paths that are available to the routing protocol, thereby providing the routing protocol an opportunity to save additional energy by using the links on which the adaptive-transmission protocol has reduced the power or increased the code rate. Such energy savings are critical for mobile communication devices with limited energy storage capability (e.g., hand-held terminals). Routing metrics provide quantitative measures of the quality and energy efficiency of the paths from the source to the destination and enable the routing protocol is to take advantage of the potential energy savings that are made possible by the adaptive-transmission protocol. We compared several routing metrics and investigated tradeoffs among energy efficiency, delay, and packet success probability.

Our most recent research has been devoted to adapting the rate of a turbo-product code that can be decoded with a commercial off-the-shelf codec chip. Parallel decoding strategies were devised, and we evaluated the resulting performance for packet transmission over channels with partial-band interference.

When coupled with the development and use of side information in the frequency-hop receiver, parallel decoding greatly enhances the performance of turbo product codes and makes them competitive with parallel-concatenated turbo convolutional codes. We devised a new method for assigning weights for soft-decision decoding, and we have demonstrated that this mechanism also provides the information needed to adapt the rate of the turbo-product code to the interference conditions on the channel. Papers based on this work were presented at the 2002 IEEE Military Communications Conference and the 2003 International Conference on Communications. A third paper has been accepted for presentation at the 2003 IEEE Military Communications Conference.

The protocol for adaptive-rate turbo coding that we devised and evaluated is suitable for wide range of codes and soft-decision decoders. In particular, the protocol can be used with binary convolutional coding or any form of turbo coding. Although our numerical results are for turbo product codes, neither the code structure nor the decoding algorithm play a role in the adaptation of the code rate. Our results demonstrate the feasibility of the adaptive-rate coding technique and the performance advantages of adaptive-rate coding over fixed-rate coding for channels with time-varying interference. In particular, the adaptive-rate coding system obtains the maximum possible throughput when channel conditions are good and it provides better throughput than fixed-rate coding when channel conditions are poor.

TECHNOLOGY TRANSFER:

Some of our early work on adaptive transmission was employed in the DARPA GloMo program as part of ITT's RAVEN project. Discussions have been held with Rockwell-Collins in Richardson, Texas, concerning the use of our adaptive-transmission protocols in JTRS. We have supplied descriptions of the protocols and performance results for Rockwell's use, and they are incorporating the concepts into JTRS. We have also discussed the use of adaptive turbo product coding for use in DARPA's Tactical Targeting Network Technology (TTNT) with Rockwell-Collins of Cedar Rapids, Iowa, and the PI served on the red team for the DARPA TTNT contractor review. Discussions were held with ITT regarding the possible use of the protocols in the SUO and JTRS programs. Several meetings have been held with personnel from MIT Lincoln Laboratory regarding the use of our adaptive-transmission protocols in future military communication satellites. A joint project is underway with Lincoln Laboratory to employ adaptive transmission with quadrature amplitude modulation and turbo product coding to improve bandwidth efficiency on wireless communication links.